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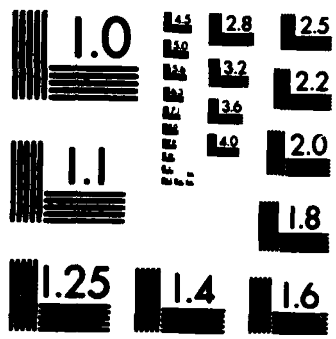

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Summary Abstract

The reporting period covers the second year of a two year program whose goal is the development and use of models of femtosecond photoconductive experiments as probes of hot carrier transport in semiconductors. The program has been extended for two more years. These experiments are being carried out in a companion effort directed by Dr. Gerard Mourou at the University of Rochester, Rochester New York. There are several main components to the modeling of such experiments. One must first model the generation of electron-hole pairs inside a semiconductor as the result of the incidence of a femtosecond optical pulse. Then one must model the processes by which the resulting current transient is developed. Lastly, the conversion of the current transient into a voltage wave transmitted down a transmission line must be understood. It is this voltage wave that is directly measured in the experiments of interest. During the first year the first two of these necessary steps were completed. During the second year these models were refined and used to study some assumptions which may be useful in the development of an experiment which can be quantitatively analyzed.

Statement of Work

For approximately 15 years there has been interest in the possibility of constructing transistors with extremely fast switching properties by

using novel features associated with charge transport in semiconductors over distances of submicron length. While there has been a large effort at theoretically analyzing these possibilities, the time and space scales are sufficiently short that meaningful experimental efforts have been precluded. Subpicosecond optical techniques may overcome this problem. The primary goal of this program is the development and use of theoretical tools for the analysis of one key example of such optical experiments.

The experiment of interest is being performed in a companion effort headed by G. Mourou of the University of Rochester, Rochester New York. In it a laser pulse is used to activate a photoconductive transient in a gap in a microstrip line on GaAs. A second pulse then is used to electro-optically sample the voltage wave triggered in this line as a result of the photoconductive transient. Both portions of the experiment are done on a subpicosecond scale thus making it the first direct probe of subpicosecond current transients in semiconductors. It differs from the vast majority of optical experiments in that information directly pertinent to the carrier momentum is collected whereas spectroscopic techniques tend to probe only carrier energy.

There are three main steps which must be performed in the development of a model of this experiment. First, we must accurately model the processes by which the laser pulse is converted into electron-hole pairs inside the gap. Secondly we must model the ensuing transport transients and their conversion into a current transient seen at the gap terminals. Lastly, we then must model the process by which this current transient is represented as a voltage wave traveling down a microstrip line as it is this

wave that is sampled in electro-optic experiments of this sort. Once the models are developed they then are to be used in conjunction with actual experiments in probes of our understanding of carrier transport on the subpicosecond scale.

Status of Research

During the first portion of the first year our efforts centered on the transformation of optical pulse data into a set of electron-hole pair generation events which are distributed over the transmission line gap in both space and time. As the transport model to be used in the second step is a Monte Carlo model, we chose to use Monte Carlo techniques for this portion as well. The result was an ability to simulate spatial, temporal and spectrally varying electron-hole pair generation events. Attention was then turned to the second problem. Here the difficulty is that while there has been a great deal of effort at developing good Monte Carlo models for electron transport in GaAs, holes have been neglected. They however cannot be neglected here. The development of a good hole model was the other main effort of the first year of the program. The hole model which was developed includes both light and heavy holes. The hole masses used are .45m for heavy holes and .082m for light holes[1]. The scattering processes include interband and intraband transitions through the mechanisms of acoustic phonon, optical phonon and ionized impurity scattering[2]. The drift velocity curves for holes show a peak velocity of 7×10^6 cm/s at 80 kV/cm.

The main task for the second year was the extension of these models into a thorough simulation of the experiment of interest. We began by exploring variations on the seminal Monte Carlo study of Ruch[3]. Ruch showed that if one suddenly stepped the electric field in a semiconductor that the electrons present would overshoot their expected final velocity value during a transient of several picoseconds duration. The optical experiments considered here however may significantly differ from the study of Ruch in that here we start with an existing field and instead create a collection of electron-hole pairs. Furthermore while these pairs will have an initial average momentum of zero they may be quite energetic if the laser wavelength corresponds to above-gap excitation. In fact we expect to see a transient in which the carrier gas is losing energy while simultaneously gaining a nonzero average momentum. We used the Monte Carlo tools to study the effects of such excitation. We found that when the electrons were excited into the bottom of the central valley that overshoots quite similar to those of a typical Ruch-like velocity overshoot study were expected. When higher photon energies were used to place electrons above the threshold for intervalley transfer changes were seen as these electrons rapidly transfer to the higher energy satellite valleys. Velocity overshoots then were seen only for relatively large electric fields and even then a smaller overshoot is expected. We also varied the temperature and found that cooling to 77 K should increase the amount of overshoot but did not dramatically increase the duration of the transient in time.

The next step was the coupling of the electron and hole transport models with Poisson's equation. The difficulty faced here is the treatment of carriers which leave the region simulated during the course of the simulation. We used a periodic boundary condition in which every time a carrier left one end of the region, it was reinjected from an equilibrium distribution at the other end. We developed a more complete methodology for treating this problem but found that for the relatively simple case considered here that the more powerful technique is not needed. The essential concept is to couple this reinjection problem with the already assumed boundary condition for the field by insuring that the induced current needed to maintain the field boundary condition through induced charges at some interface be consisent with the current associated with the net flow of carriers in and out of the region of simulation.

Once the boundary condition issue was resolved the crucial question which we asked was whether or not the fields and carrier densities would be significantly inhomogenous during the early transient. Such homogeneity was assumed by Ruch and would greatly simplify the interpretation of any experiment. We found that at least in a one-dimensional model homogeneity is expected. We then coupled the photoconductive gap simulated by Monte Carlo techniques to the transmission line and compared our results with those of experiment. Qualitative agreement was obtained.

There are several main scientific questions which we hope to answer. The first is the nature and existence of velocity overshoots of carriers suddenly introduced to a high electric field in a semiconductor. All transport calculations that allow for this possibility predict it yet no

unambiguous experimental observation of such an overshoot has been made. Our goal is to use these techniques in an effort at performing such an experiment. We have made good progress in establishing an effective experimental protocol. High quality material must be used and effective contacts to it must be made. It is important that a low excitation experiment be carried out in which difficulties associated with substantial temporal variations in the voltage across the photoconductive gap, strong carrier-carrier interactions and the generation of nonequilibrium phonons are avoided. The sensitivity of the electro-optical sampling technique should allow this to be possible.

Even in this protocol we face a difficulty. The desired transport transient is convolved with the capacitive response of the gap. We will use an extension of Auston's model[4] of these experiments as a basis for understanding how the deconvolution is to be performed. Here the Monte Carlo models will play an important role. We will simulate an experiment and then use our proposed data analysis techniques on the waveforms generated by the simulation. The answers obtained will be compared with the stored details of the actual transient response of the gap during the simulation. Such a test is useful as deconvolution is an ill-posed problem.

A second important question involves the role of intervalley scattering in such experiments. The intervalley coupling coefficients are extremely important parameters and yet are difficult to either measure or compute. It may be possible to probe these processes by choosing laser energies that

introduce carriers into the conduction band at the level of the satellite valley minima.

A third set of questions involve the role of carrier-carrier scattering. Optical experiments offer one vehicle of studying these interactions without the possible competing effects of increased doping density and associated ionized impurity scattering.

We also will be investigating the utility of such techniques as a basis for high-speed device characterizations. The first question here will be the development of an effective equivalent circuit model for the photoconductive response of the gap. This is closely related to the development of methods of extracting transient transport data from the photoconductive experiment. The second main question is the use of such techniques as a vehicle for determining the S-parameters of high frequency transistors. Here we will first use analytical models in which both the transient time-domain response and the sinusoidal steady-state S-parameters are expressable in closed form. The second feature will be the use of a SPICE based, time-domain GaAs MESFET circuit model for which the S-parameters are known. We will simulate the transient experiments and investigate various techniques for extracting S-parameters from the time series data.

Professional Personnel

Christopher Caruso is a graduate research assistant working on this program. His undergraduate degree is in Electrical Engineering from General Motors

Institute, Flint MI. He presently is a graduate student in Electrical Engineering at Arizona State University and anticipates the completion of his masters degree in November 1986.

Dr. Robert O. Grondin is an assistant professor of Electrical and Computer Engineering at Arizona State University and the principal investigator of the present effort. He received the BS, MS and Ph.D. degrees in Electrical Engineering from the University of Michigan. He was a post-doctoral fellow at Colorado State University prior to his acceptance of his present faculty position in 1983. In 1985 he was named a Presidential Young Investigator by the National Science Foundation.

Interactions

As reported in the first year a strong interaction has developed between this effort and the companion experimental effort at the University of Rochester. All of the personnel described above have visited the experimental site and regular communication via telephone, letter and running into each other at conferences has developed. During the second year this form of interaction has continued to grow. In the upcoming years this will also be augmented by the URI on ultrafast electronics which has been established jointly at Rochester and Cornell.

Another strong interaction noted during the first year was one developed between the investigators on this project and others who are performing investigations into transient carrier transport at Arizona State

University. This has greatly aided in the development of the Monte Carlo models. Several of the other investiagtors have now graduated and are located at the University of Illinois and at Scientific Research Associates in Glastonbury Connecticut. Both continue to be actively involved in this general activity.

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